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A Quantum Adaptive Importance Sampling Algorithm for Multidimensional Integration

Perturbative Quantum Field Theory is central to perform accurate theoretical predictions of observables at high-energy colliders. Fundamental concepts in this framework, such as loop Feynman diagrams and the phase-space, involve evaluating multidimensional integrals that are computationally intensive due to divergences and complex mathematical structures. To address these challenges and improve the precision of such calculations, the standard approach relies on adaptive importance sampling. The most notable example is the VEGAS algorithm, which adaptively updates a multidimensional grid. However, because the computational cost of handling each grid cell grows exponentially with the number of the integral's dimensions, the model for the probability density function (PDF) is simplified to a separable product of PDFs, factorized (or projected) along each integration variable's axis.

In this work, we present a Quantum Algorithmic workflow that performs Quantum Adaptive Importance Sampling. The workflow consists of three main elements. First, the Encoding part, in which the integration domain is discretized, and mapped into a quantum circuit. In this step it is also crucial to choose a suitable parameterized quantum circuit architecture, with adequate expressivity to efficiently capture all the complexities of the structures of the target integrand. Second, the State Preparation stage, where by adapting the parameters of the quantum circuit, we shape the PDF generated by the quantum state to approximate the desired target integrand. Third, the outcomes of the optimal circuit's quantum state tomography are processed within a dedicated statistical framework. This framework is an adjusted version of standard importance sampling to a quantum computational system, that fulfills the quantum state tomography constraints while preserving its inherent unbiased estimation.

The central objective is to manipulate the grid in it's entirety via the quantum circuit in order to bypass the limitations of the separable PDF assumption.
Thus, being able to sample from the proposal PDFs that approximate the target integrand with higher accuracy.
As an application, we look on benchmark integrals and loop Feynman integrals, and compare the precision that the best grid of VEGAS gets against that of the quantum generated proposal PDF, as a function of the number of samples.

Secondary track

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